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FEASIBILITY STUDY FOR DESIGN OF A BIOCYBERNETIC COMMUNICATION SYSTEM,

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Prepared for:

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Attention: DR. GEORGE LAWRENCE, PROGRAM MANAGER

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CONTENTS

TABLES

ILLUSTRATIONS

Summary

This project was initiated to test the feasibility of designing a close-coupled, two-way communication link between man and computer using biological information. Specifically, experiments have been devised to determine whether biological information can be related to human thought, whether this information can be processed meaningfully by a computer, and whether similar biological processes representing the same or other thoughts can be induced in the same or another individual. Should such a close-coupling between man and machine prove to be feasible, possible applications would include extremely rapid interactive processing between a man and a computer, or communication between two or more persons with the computer acting as an interface.

The research plan was predicated on existing evidence that verbal ideas or thinking are subvocally represented in the facial muscles of the vocal apparatus (see Rationale of Approach, p. 3, for details). If the patterns of this muscle activity are at all similar to those involved in normal overt speech, then it is reasonable to assume that the electrical activity of the brain during covert speech (verbal thinking) may be similar to that during overt speech. The objective of the first year of research is to establish the validity of this basic premise.

The general methodology was to record the electromyograph (EMG) of facial muscles involved in speech from volunteer human subjects during performance of language tasks. The electroencephalograph (EEG) from scalp electrodes overlying areas of the cerebral cortex involved in speech were recorded simultaneously (see Methods, p. 5, for details). The resulting analog data were then digitized for computer processing, and several statistics that reveal patterns of cortical activity were calculated. These statistics were then used in a computer pattern recognition program designed to identify features in the physiological data associated with specific words, whether overtly or covertly produced.

Two experimental paradigms were used (see Results: Experiment 1, p.13, and Results: Experiment 2, p.29, for details). In the first, EMG and EEG records were obtained during performance of a language task under various conditions of stimulus presentation including: visual presentation, overt response; visual presentation, covert response (silent reading); auditory presentation, eyes open, overt response; and auditory presentation, eyes closed, overt response. (The last two conditions were chosen because the EEG is characteristically different when the eyes are open compared with closed.) The language task, recommended by a psychophysiological linguist consultant, consisted of words and sentences most likely to reveal patterns in the EMG and EEG that may be related to speech and verbal thinking. In the second experiment, similar records were obtained, but under slightly different stimulus conditions and with 20 repetitions per subject for reliability tests. These conditions included visual presentation with overt response of five selected monosyllabic words, and five bisyllabic words with the accent first on one syllable and then on the other to compare ordering effects caused by emphasis.

Computer processing of these data has not been completed, but significant results to date are:

(1) EMG patterns for each word are specific for that word.

(2) EMG patterns for a given word are consistent, showing less within subject variability than between subject variability.

(3) Averaged EMG patterns for a given word spoken by a given individual are sufficiently consistent for that averaged EMG to serve as a template for identifying the same word when it is imbedded in a sentence.

(4) There is some variability in EMG patterns for bisyllabic words between accent on the first or second syllable, but it is sufficiently small so that either pattern may be used to identify the same unaccented word imbedded in a sentence.

(5) "Raw" EEG patterns for silently read words are similar to those for the same overtly read words, so that the onset and ending of silent reading may be identified by visual observation. This strongly suggests that the statistical data of the EEG during verbal thinking should be similar to the statistical data of the EEG during vocalization of the same thought.

(6) The pattern recognition analysis so far carried out has been able to distinguish words beginning with "H" from all other words, and to define five clusters for five word sets.

In conclusion, the results so far show that the EMG may be used to identify specific overtly spoken words of a given individual. The results also imply that patterns of EEG activity associated with these words may be used to identify the same word when covertly produced (as in verbal thinking). Completion of the EEG computer pattern recognition analysis during the remainder of this contract year should definitely establish the validity or nonvalidity of this implication. Research during the second year will examine all possible EEG locations to identify those that best serve to make such identifications on-line.

No important items of equipment were purchased or developed during this period, and there were no major technical problems.

Introduction and Significance of Research

This project was initiated to test the feasibility of designing a close-coupled, two-way communication link between man and computer using biological information. Specifically, experiments have been devised to determine whether this information can be processed meaningfully by a computer, and whether similar biological processes representing the same or other thoughts can be induced in the same or another individual.

Should such a close-coupling between man and machine prove to be feasible, possible applications would include extremely rapid interactive processing between a man and a computer, or communication between two or more persons with the computer acting as an interface. For example, an individual using such a biocybernetic communication system would be able to "talk" (i.e., both send and receive) with a computer at the speed of thought, rather than be limited by the speed of a teletype or other electromechanical device through which ideas in the form of questions and answers must normally pass. In addition, nonverbal imagery and affective (emotional or "feeling") states might similarly be used in the communication process, thereby significantly increasing the bandwidth of information transfer. Furthermore, two or more individuals, separated by short or long distances, would have the capability of rapid and accurate communication with a high degree of immunity to decoding if the signals were intercepted, where information transfer might be more complete than with normal speech.

Rationale of Approach

Our approach is predicated on previous research conducted by the authors and others in the areas of psychophysiological measures of thought, computer processing of electrophysiological information, and development of computer pattern recognition techniques. This research may be summarized as follows (see SRI Proposal LSU 71-145 to DARPA, dated 10 December 1971, for details).

Early work by Watson (1930) indicated that verbal cognitive processes may be represented in muscle activity of the vocal apparatus as subvocal speech. McGuigan (1970), reviewing studies of such covert oral behavior during the silent performance of a language task, concludes that covert oral behavior (as measured by the electromyograph, or EMG) increases significantly in amount and frequency of occurrence. Thus, verbal ideas or thinking, although unquestionably a central nervous system process (MacNeilage and MacNeilage, 1971), has some sort of peripheral representation in the muscles of the vocal apparatus.

If the patterns of this muscle activity are at all similar to those involved in normal overt speech, then it is reasonable to assume that the electrical activity of the brain during covert speech, or thinking, may be similar to that during overt speech. That is, a measure of the scalp-recorded electroencephalograph (EEG) of a human during verbal thinking should be similar to the EEG of the same individual when expressing the same thoughts vocally.

However, examination of the "raw" EEG has not revealed any obvious pattern related to overt or covert speech; it may be that only patterns of EEG activity between various areas of the brain at a given moment are related to speech. Several technical advances made in recent years have provided us with some tools to deal with this possibility. Most important is the use of computer techniques for frequency analysis of the real-time EEG and the development of multivariate statistical procedures (Donchin and Lindsley, 1966; John et al., 1964; and Rose and Lindsley, 1965). These procedures allow comparison of specific components of EEG waveforms that are known to reflect different neurophysiological processes. In addition, certain statistics, such as auto- and cross-sprectral frequency analysis (Walter, 1963; Walter and Adey, 1965), linear coherence function (Adey, Kado and Walter, 1967), and the weighted-average coherence (Galbraith, 1967), may be used to determine the degree of interaction between two different brain regions. Thus, with these tools, the EEG waveforms from several areas of the brain that are neurophysiologically related to speech may be examined to determine if their patterns or interaction are similar during overt speech and verbal thinking.

A thorough visual analysis of the statistical results of these EEG waveforms would be extremely complicated and time-consuming; certainly on-line visual analysis of verbal thinking would not be possible. Therefore, we have turned to machine pattern recognition techniques to analyze the patterns of the EEG interrelationships to be found in the cross-spectra and coherence functions related to covert and overt speech. Most useful for this feasibility study are techniques for on-line pattern recognition using interactive graphic displays (Hall et al., 1968). These techniques allow the user to process multivariate data by using all reasonably conceivable graphic plots, and further manipulate the data using appropriate numeric procedures available in the computer system. Thus, for our purposes, a set of statistics such as the coherence functions of the EEG, the patterns of the EMG changes with overt speech, and other measures may be plotted as a function of each other for specific covert language tasks (i.e., thinking).

The objective of the first year of this feasibility study, then, is to establish the validity of the basic premise that patterns of biological information can be related to covert language behavior. This is being done by:

(1) Measurement of EMGs of the vocal apparatus and EEGs overlying cerebral areas involved in speech during overt and covert language tasks.

(2) Computer processing of the averaged biological activity, and analysis of the cross- and auto-spectra, coherence, and weighted-average coherence of the EEG as related to EMG speech patterns.

(3) Application of computer pattern recognition techniques to determine if the statistical patterns of biological activity from the EMGs and EEGs are similar during overt and covert speech, and to attempt to machine-identify silent language performance with the pattern recognition method.

Methods

General

Data Collection. The data have been collected and analyzed as follows. During performance of a language task, integrated EMGs from surface-recordable muscles of the human face involved in speech production are recorded along with the instantaneous EEG from places on the scalp overlying brain regions involved in speech. Integrated EMGs, with a time constant of 0.25 sec, were chosen over instantaneous EMGs because of the limited band pass of the recording system (a Beckman type R Dynograph), because of the relative ease of quantification of EMG activity, and because integrated patterns of EMG changes related to speech are more readily identifiable visually and by machine.

The language tasks are described in detail below. In brief, they consist of the human subject being presented visually or auditorily with selected individual words or sentences, in response to which the subject speaks the word or sentence overtly or reads it covertly as instructed.

The output of the Beckman recorder is simultaneous on eight channels of ink-writing, moving paper (at 25 mm/sec) and on an Ampex SP-300, seven channel analog instrument tape recorder with FM and AM capability. The Beckman chart recording is used for real-time monitering of signal levels and for later editing of the Ampex analog tape. Six channels of EMG and EEG and one channel of voice are recorded on the analog tape.

Data Analysis. Data are analyzed in three ways. The first is direct overlay tracings of the EMG outputs on the Dynograph recorder. Overlays of various EMG placements are visually compared for within-word pattern variability, between word variability, between subject variability, between experimental conditions variability, and between experimental sessions for reliability of patterned EMG production.

Linc-8. The second and third methods of analysis are not yet fully operational, but are proceeding as follows. In the second method, the Ampex analog tape is edited and digitized by a Linc-8 computer; the seven channels of edited data are then stored on Linc tape for further processing. A data block consists of five seconds of recording: the three seconds before the stimulus word presentation, one second for the overt or covert response, and one second of post-response activity. Six months have been spent writing the Linc-8 programs necessary for this data digitization and storage process; the program is now complete, and data are being edited and stored.

Several other processing procedures also will be done on the Linc-8. One procedure is to transfer the stored edited data from Linc tape to a digital tape recorder for further processing on a CDC-6400 computer (see below). This recorder will be installed during October; programs for the data transfer are now being written, and complete transfer capability of edited data to the CDC-6400 should exist by December.

This will reduce our turn around time from about one month at present to no more than one day (i.e., the time from initial data collection to complete computer analysis and some pattern recognition).

Other procedures on the Linc-8 will include averaging of EMG and EEG responses during overt and covert speech. These averaged responses will then be used with a simple pattern recognition program (now being written), whereby a single analog response to a test stimulus word will be compared with the averaged response of a standard stimulus word. The comparison word response will be normalized and scaled on the Linc-8 scope for a visual "best fit" to the standard word response. Point-by-point comparison of the two displays will then be made using a variance analysis. If the sum of the point variances is below a certain value (determined by the variance of the averaged response), then the comparison response will be identified as belonging to the same word as the averaged response. The reliability of this method can then be checked by computing an error score of all comparisons. If the reliability is high, this procedure will be tried on the CDC-6400 for pattern recognition of the analog waveform.

CDC-6400. The major portion of data analysis will consist of calculating the various statistics for the EMG and EEG data, including cross- and auto-spectra, linear coherence, and weighted-average coherence. These statistics will then be used in the clustering procedure for pattern recognition. Clustering is a means of grouping data so that similar objects or samples fall in the same group and dissimilar objects or samples fall in different groups.

ISODATA, the name of the clustering program, uses Euclidian distance as the measure of dissimilarity. Thus, objects that are far apart are assigned to separate clusters, and objects that are close together are put in the same cluster. The values of the variables in a data set must be scaled to the same relative order of magnitude so that they have equal effect in the clustering. For example, the distance between the points at coordinate (1000,5) and (1100,6) is 100. No significant contribution is added by the lower-scaled values 5 and 6.

The data were processed both with and without scaling. In the output of the EEG and EMG spectral analysis programs, it is observed that the amplitudes are much higher for the lower frequencies, from 0-4 hertz. Thus, clustering of the unscaled spectral data is based mainly on these lower frequencies. In scaling the data, two different methods have been used. First, amplitudes of spectral data are scaled to proportion, so that each variable (i.e., each spectral bin) is normalized to a standard deviation of "one" over all words. Second, each spectral bin is scaled to a standard deviation of "one" over all pairs of recorded data channels and all stimulus words. Use of this technique with the actual data is described below.

Subjects and Experiments

Subjects were three adult, right-handed, human female volunteers, ages 21-41, hereinafter designated B, C, and D. A total of 16 experimental sessions, each of about 2½ hours duration, were carried out under two experimental paradigms. A given session for a given subject is identified by the subject's letter code and her chronological session; thus C5 was the fifth experimental session for subject C. Before conducting these sessions, several apparatus debugging sessions were carried out with a fourth subject, A.

Experiment 1 was concerned with establishing optimal values for all experimental parameters. Thus, various electrode placements for both EMG and EEG were used to determine optimum placements for obtaining reproducible patterns of surface-recordable muscle activity of the vocal apparatus and the EEG related to overt speech. In addition, various words and sentences suggested by our psychophysiological linguist consultant were employed to determine the best language task. For Experiment 1, subjects B and C were run four sessions each and subject D for two sessions.

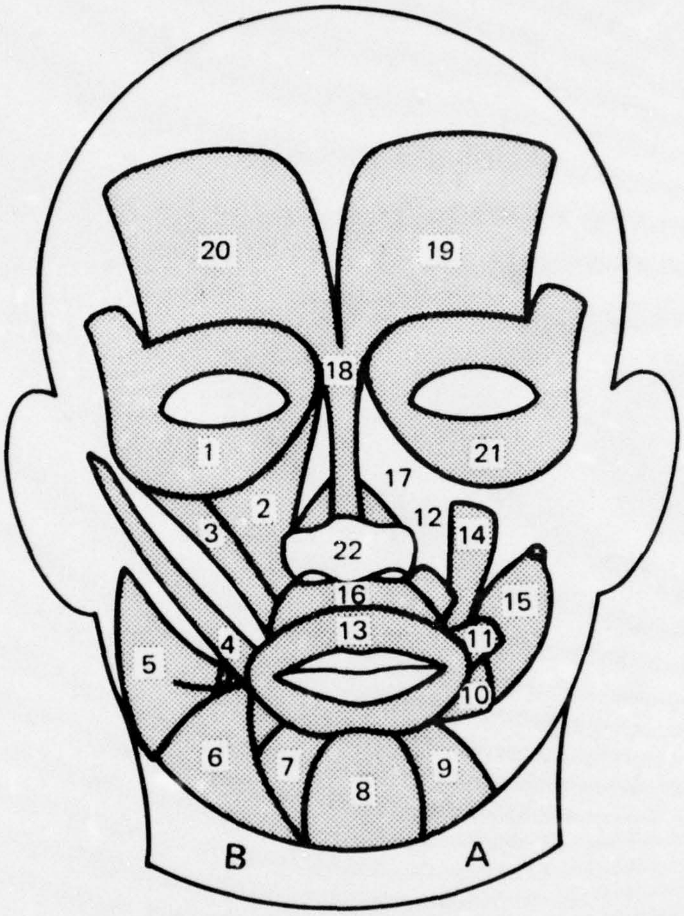
Experiment 2 was a further refinement of Experiment 1. Only those electrode placements used in Experiment 1 that gave optimal results were employed for further recording. Certain words from the language task were selected that would most likely result in reproducible EMG and EEG patterns. Furthermore, the sessions were more rigidly structured, each session consisting of ten repetitions of the language task. For Experiment 2, all three subjects were run two sessions each.

Apparatus

Electrodes and Electrode Placements. For surface recording of the EMG from facial muscles involved in speech production, Beckman silver, silver-chloride miniature disk skin electrodes (2-mm exposed) were used. EEG scalp electrodes, reference electrodes, and the ground electrode were Beckman silver, silver-chloride standard disk skin electrodes (8-mm exposed). Two reference sites were employed--the skin under the left mastoid for EMG recordings and the skin under the right mastoid for EEG recordings. All recordings were monopolar in order to record absolute potentials at the recording site and to eliminate in-phase signals common to two electrodes.

Selected skin areas were first cleansed with acetone (alcohol on the face) and then conditioned with Redox electrode paste by rubbing it into the skin, followed by a second cleansing of acetone. A conductive, paste-filled electrode was then placed over each recording area and attached by a sticky collar to the underlying skin. Following a recording session, electrodes were removed, and the skin was cleaned with acetone or alcohol.

Figure 1 shows the facial musculature. Muscles involved in vocalization that are surface-recordable are 2, 3, 4, 6, 7, 8, 9, 10, 11, 13, and 16. Each of these locations was tested during preliminary experiments,



1. Orbicularis oculi m. (right)
2. Quadratus labii superioris m. (right)
3. Zygomatic head of quadratus *labii superioris m. (right)*
4. Zygomaticus m. (right)
5. Risorius m. (right, cut)
6. Triangularis m. (right)
7. Quadratus labii inferioris m. (right)
8. Mentalis m.
9. Quadratus labii inferioris m. (left)
10. Triangularis m. (left, cut)
11. *Zygomaticus m. (left, cut)*
12. Quadratus labii superioris m. (left, cut)
13. Orbicularis oris m.
14. Caninus m. (left)
15. *Buccinator m. (left)*
16. Depressor septi nasi m.
17. Nasalis m. (left)
18. Procerus m.
19. Frontalis m. (left)
20. Frontalis m. (right)
21. Orbicularis oculi m. (left)
22. Nasalis m. (right)

FIGURE 1 MUSCLES OF THE FACE (AFTER VAN RIPER AND IRWIN, 1958)

and 2, 9, and combined sites 7/8 and 13/16 were selected for Experiment 1 as representative of the muscles most used in speech production of the test words (see below). For Experiment 2, a single electrode was placed over muscles 13/16 and another over muscles 7/8 based on the results of Experiment 1 for best EMG speech-pattern production.

Figure 2 illustrates the 10/20 system of EEG recording (Penfield and Jasper, 1954). Locations F7, T3, C5, F8, T4, C6, and T6 were employed in Experiment 1. These approximate placements over cortical areas assumed to be involved in speech production (Penfield and Roberts, 1959) as follows. For the dominant hemisphere, F7 (Broca's speech area); C5, control of vocalization musculature; T3 and T5, speech organization and comprehension were used. For control, the nondominant hemisphere placements F8, C6, T4, and T6 were employed. In Experiment 2, placements F7, T5, and C5 were used for the dominant hemisphere and T6 for the control.

Equipment. Apparatus for Experiments 1 and 2 was the same; only the electrode placements and procedures differed. Electrodes from the facial musculature were led first to a Beckman Model 9852A EMG integrator coupler, with a time constant of 0.25 seconds, and pass band of 20-5000 hertz. Experiment 1 used channels 1, 2, and 3 of the Dynograph to record the integrated EMG. EEG electrodes were led to Beckman type 9806A couplers, with a pass band of 2 to 30 cps; channels 4, 5, and 6 recorded the instantaneous EEG. Channel 7 recorded the voice output of the microphone; channel 8 was not used.

All physiological signals were preamplified by Beckman Model 481B preamplifiers, and were then led simultaneously to Beckman Model 482A power amplifiers with calibrated zero suppression, and to an Ampex SP-300, seven channel, analog instrument tape recorder. The output of the Beckman power amplifiers drove ink-writing galvanometers on moving chart paper at 25 mm per sec. The output on the chart paper could be set by a switch to record either the input to the Ampex tape recorder (i.e., "direct" recording) or the output of the Ampex; this feature enables the investigator to calibrate and monitor the permanent tape recording. EMG and EEG recordings were on channels 1 through 6 of the Ampex, using frequency modulation at 1-7/8 inches per sec (pass band dc-312 hertz). Voice was recorded on channel 7 using amplitude modulation (50-3.5 kilohertz).

Data from Experiments 1 and 2 filled three 10-½-inch Ampex tapes with analog data. Some of these data were then sent through the data analysis system (see above), using the Linc-8 laboratory instrument computer, an XDS 930 computer, and finally a CDC-6400 computer (see Data Analysis section below).

Procedure

Language Task. Experiment 1 used 16 words and three sentences (Table 1) as the language tasks (the words used in Experiment 2 are described under that section). Individual words were chosen on the basis of several criteria. According to our psycholinguistic consultant, the

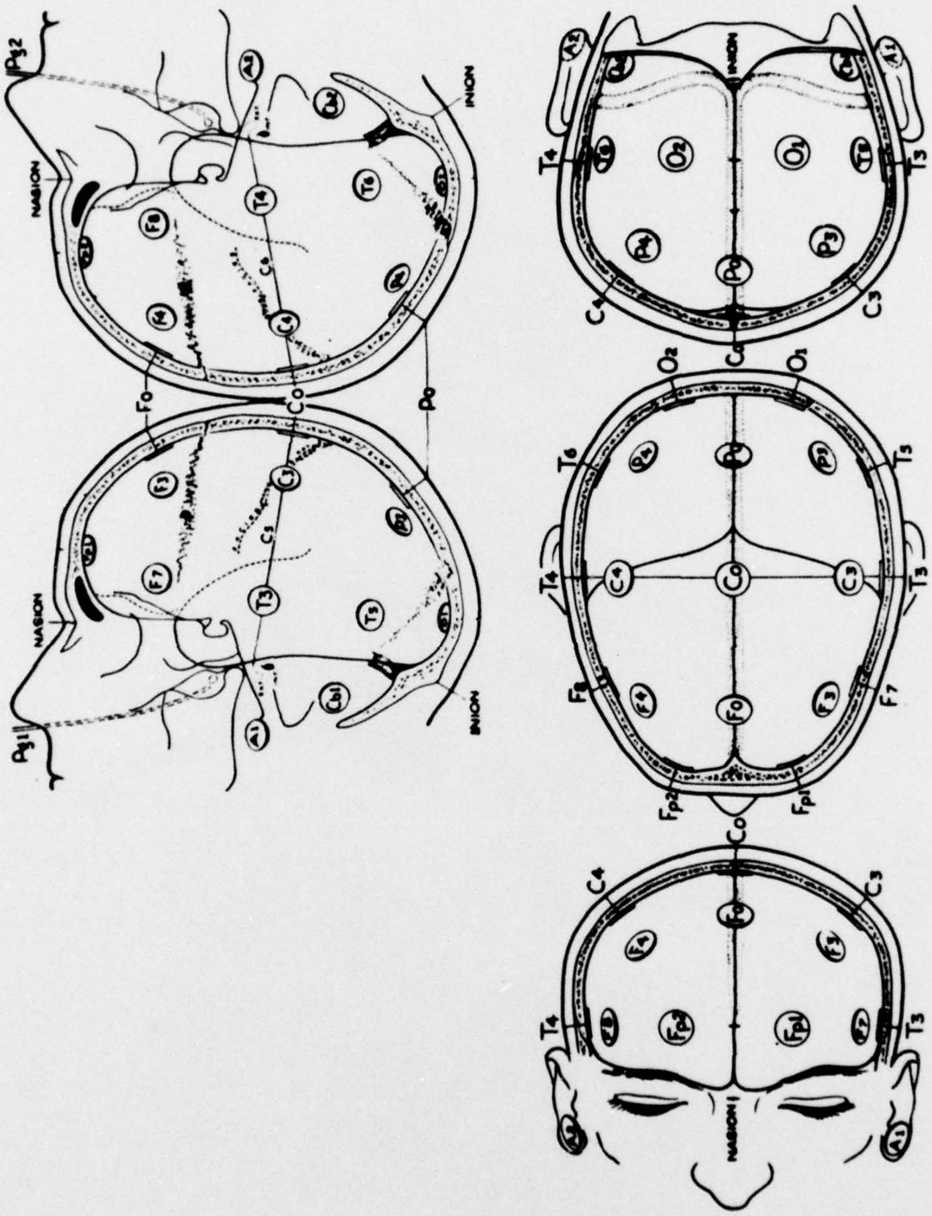


FIGURE 2 ELECTRODE PLACEMENTS FOR 10/20 METHOD OF EEG RECORDING (AFTER PENFIELD AND JASPER, 1954)

Table 1

PURE VOWELS, DIPHTHONGS, AND SENTENCES USED IN EXPERIMENT 1

Pure Vowels

No.	Word	Vowel or Diphthong	Lips
1	heat	ee	Spread
2	hit	i	Spread
3	head	e	Open
4	had	ae	Very open
5	the	uh	Spread
6	bird	er	Bilabial
7	father	ah	Spread
8	call	aw	Spread
9	put	u	Bilabial
10	cool	oo	Round
11	ton	ʌ	Open

Diphthongs

1	tone	ou	Round
2	take	ei	Spread
3	might	ai	Bilabial
4	shout	au	Round
5	toil	oi	Round

Sentences

1. "PIMPLES AND POCKMARKS MAR PULCHRITUDE IF PROMINENT ON PARTS WHICH ARE DISPLAYED TO THE PUBLIC."
   (16 bilabials, underlined; 15 words)
2. "CRANK PHONE CALLS CAN IRRITATE ONE ALTHOUGH THEY ARE NOT AS DANGEROUS AS PHYSICAL ASSAULT."
   (3 bilabials, underlined; 15 words)
3. "NOW IS THE TIME FOR ALL GOOD MEN TO COME TO THE AID OF THEIR COUNTRY."

main aspects of vowel production that have recordable consequences from the EMG on the surface of the face area are: (1) lip rounding and (2) lip opening. The lip opening action is most marked when there is a preceding bilabial or bilabial consonant (e.g., p, b, m). For consonant production, the main aspects are: (1) lip closure (2) lip spreading and (3) lip rounding. Therefore, for this experiment, we chose words that were most likely to have these characteristics, and a few words that did not have them for contrast.

The first 11 words in Table 1 represent the pure vowels, which means that their quality is unchanged throughout the syllables in which they are employed. In addition, these vowels represent the different tongue positions for the principal English vowels (Denes and Pinson, 1963), and therefore give a change in vocal musculature without changing the balance of their quality in a syllable. Thus, the EMG recordings should reflect differences based only on tongue position, and whether the lips are spread, rounded, unrounded, or bilabials (see Table 1 for significance of each word). The last five words in Table 1 are diphthongs, whose qualities do change from the beginning to end in the syllable in which they are used, thus offering a contrast for the EMG measures of pure vowel pronunciation. Tongue movements of the diphthongs are between those for pure vowels. Diphthongs also have bilabials, lips rounded, and spreading lips.

Similarly, the sentences were chosen to reflect (1) the predominant use of bilabials, (2) the predominant use of nonbilabials, and (3) a control sentence. In addition, each word of each sentence was spoken separately, as well as the sentence being spoken naturally, to compare the EMG pattern of each word in the sentence in its "pure" state with its EMG pattern when the word is preceeded and followed by another word.

After electrodes were attached, Ss were comfortably seated in a semi-dark, electrically shielded booth. All electrodes were plugged into a junction box leading to the Beckman Dynograph recorder. Electrode resistances were checked; if one was found to be greater than 5000 ohms, it was removed, the skin further cleansed and conditioned, and the electrode replaced. When all electrodes checked correctly, the S was instructed in the experimental procedure, a microphone for recording speech was placed in front of the S's mouth, and a recording session was begun.

Stimulus Presentation. Each of the individual words and each sentence in Table 1 were printed on a 35-mm slide (white on black to reduce glare) and presented to the subject by projecting the word (or sentence) on a rear projection screen about 3 feet from the subject's eyes. The subtended visual angle of the stimulus and its intensity in the semi-darkened room were chosen to avoid squinting, glare, or eye strain. The procedure for stimulus presentation was as follows.

After installation in the recording chamber, the S was instructed that she was to relax with eyes closed while the polygraph and tape

recorder gains and filters were adjusted for proper EMG and EEG recordings. During that period, the S was to say her name when asked (to calibrate EMG gains and the voice channel) and to open or close her eyes when asked (to check for alpha in the closed-eyes EEG and alpha blocking, or desynchronization, with eyes open). Following these adjustments, the S was told she would be presented with a list of 16 words, one at a time, for four full presentations, plus three sentences for two of the presentations. The first presentation would be visual. (The S was shown a test word on the screen as an example.) The S was to sit relaxed with her eyes closed. On hearing the statement "ready" from the experimenter, she was to open her eyes and look at the screen. In 2-3 sec, a stimulus word would be projected on the screen for about 3 sec, during which time she was to read the word aloud into the microphone. When the projected word was turned off, she was to close her eyes until the next word was presented, and wait until the next "ready" signal.

At the end of the 16 words, the three sentences were presented to her twice each, one at a time. On the signal "ready," S was to open her eyes and look at the screen. When the sentence appeared the <u>first</u> time, she was to read it aloud one word at a time at the same speed as the preceding individual words. On the <u>second</u> presentation of the sentence, S was to read the sentence at her natural speech. The second and third sentences were to be read in the same way. (All words and the three sentences were presented in a random order to obviate any anticipatory effects in the EMG and EEG.)

At the end of the first presentation, the S was instructed that the same series would be shown as before, except that this time she was to read the word (or sentence) <u>silently</u>. On the third and fourth presentations, the S was instructed that only the 16 words would be presented, not the sentences, but that this time the words would be called to her by the experimenter (auditory presentation), and she was to repeat the entire list with her eyes remaining open, while on the fourth presentation she would keep her eyes closed. This procedure was used to discriminate between an auditory and visual stimulus and between eyes open (a desynchronized EEG), and eyes closed (a synchronized EEG).

Subjects B and C participated in four complete sessions each over two months to test repeatability within a S and variation between Ss. Subject D was given two complete sessions during the same period. Since only seven channels of recording were available and 14 total electrode placements used, several trials were repeated for each S using those electrodes not previously recorded from.

Results: Experiment 1

General

Figure 3 illustrates a typical Beckman Dynograph recording for the period of visual presentation of a single stimulus word ("TOIL"), and the overt response during the third session for subject C. Although such a

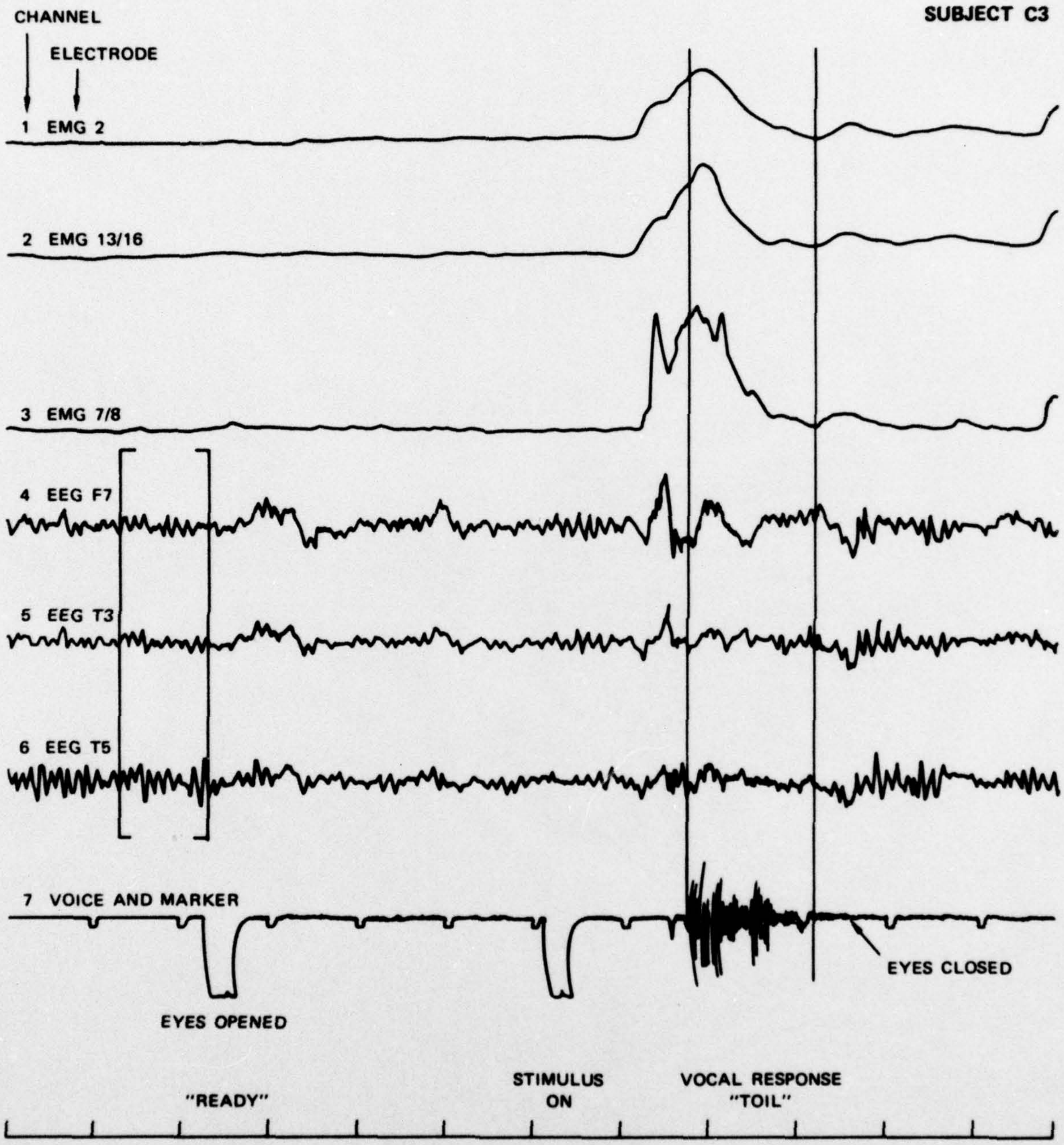


FIGURE 3 DYNOGRAPH RECORDING OF STIMULUS-RESPONSE OF EMG AND EEG FOR THE WORD "TOIL"

"raw" record does not provide much information, several items of interest may be noted that are generally present for all stimuli and overt responses in both Experiments 1 and 2.

First, note in channels 4, 5, and 6 that the EEG is synchronized at about 9 hertz (alpha rhythm) one sec before the "ready" signal (shorter bracketed area). However, following the ready signal, this synchronization is significantly reduced. Shortly after the stimulus word is presented, and before the beginning of the vocal response, all three EEG traces become completely desynchronized (alpha "blocking"), and remain so until the eyes are closed about ½ sec after vocalization is complete. This means that under these conditions, the EEG spectra during speech will consist of primarily "fast" frequencies (roughly 15-30 hertz).

Second, note the time relation between the physiological measures and the complete vocal response (longer bracketed area). In channels 1, 2, and 3, the integrated EMG begins to increase about three-fifths of a second before actual voice production (channel 7), and continues for a short time after the vocalization ends. In the EEG, coincident with the onset of the EMG increase, there is a large "slow-wave," negative/positive potential. Although not always present, it does occur frequently. Because this negative/positive shift (largest in channel 4) is so large, because it occurs over a second after the visual stimulus comes on, and because it is not always present, it cannot be considered a visually evoked response. This is clearly evident when comparing Figure 3 with Figures 4, 5, and 6, which illustrate the same response ("TOIL") with audio presentation (eyes open and closed and overt response) and during silent reading (covert response).

Other comparisons of note between these figures are the EEG during audio presentation, overt response, eyes open (Figure 4), versus eyes closed (Figure 5). In Figure 4, desynchronization of the EEG is much the same as in Figure 3, whereas in the eyes closed condition (Figure 5) desynchronization is only slightly decreased in channels 5 and 6 and not at all in channel 4. Therefore, the spectra between eyes closed and eyes open should be different. Nevertheless, the temporal characteristics of the physiological responses relative to the onset of vocalization discussed above are present in both conditions, including the slow-wave, negative/positive potential in the EEG.

In Figure 6, during visual presentation but with a covert response, there is relatively little change in the EMG (the gain of channels 1, 2, and 3 is 100 times that in Figures 3, 4, and 5). In the EEG, however, the slow-wave potential still appears (between brackets), although not as sharp as during actual vocalization. Since there is little or no EMG activity, even at high gain, this EEG potential cannot be caused by muscle action. Also, since the temporal realtion between this slow-wave and the onset of vocalization in Figures 3, 4, and 5 is consistent, then the probable onset of silent reading can be predicted from Figure 6. Of course, the EEG of Figure 6 contains the same temporal relations of synchronization and desynchronization relative to the ready signal, onset of the stimulus,

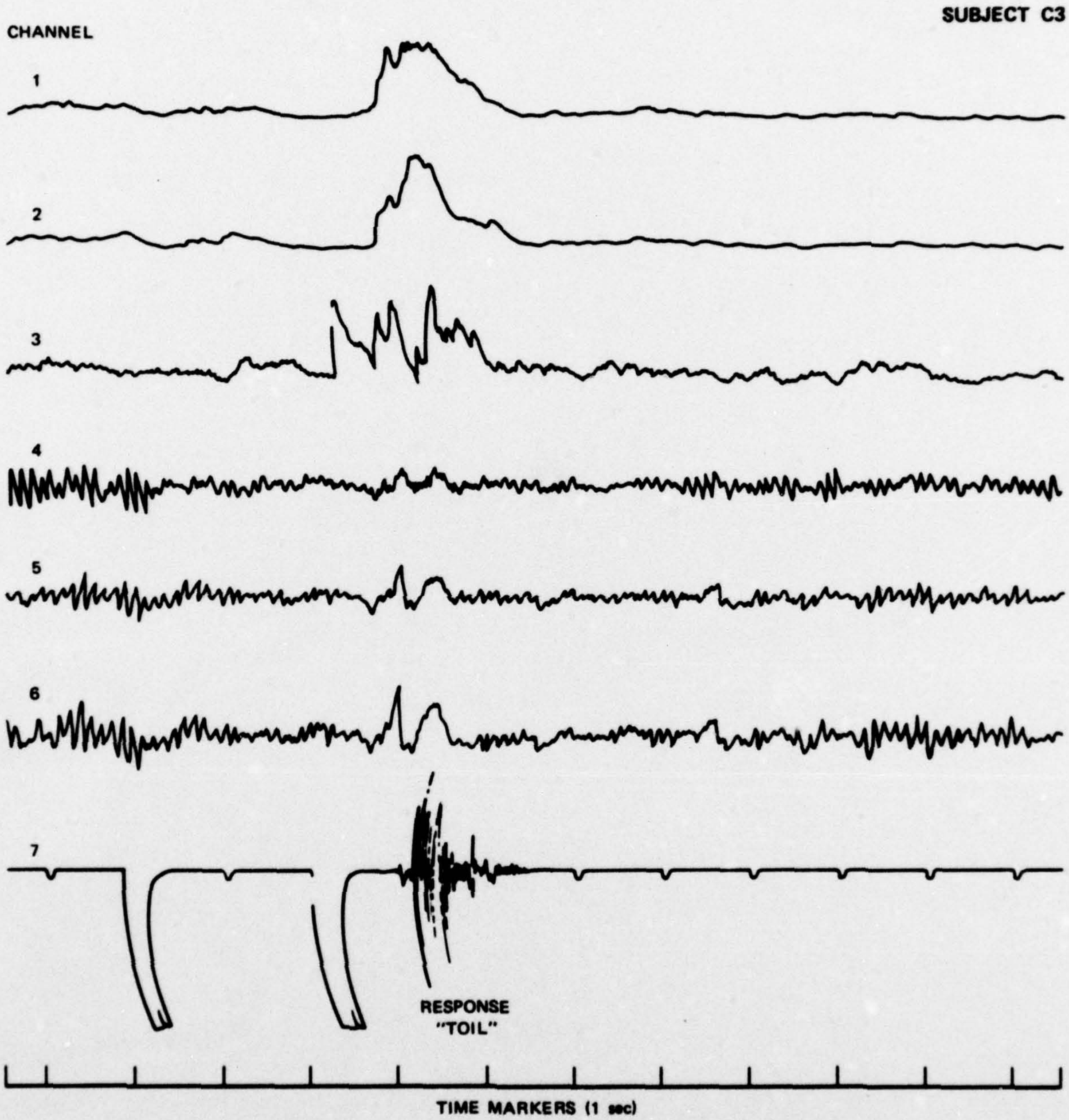


FIGURE 4 DYNOGRAPH RECORDING OF RESPONSE TO AUDITORY STIMULUS, OVERT RESPONSE, EYES OPEN. Electrodes and symbols the same as Figure 3.

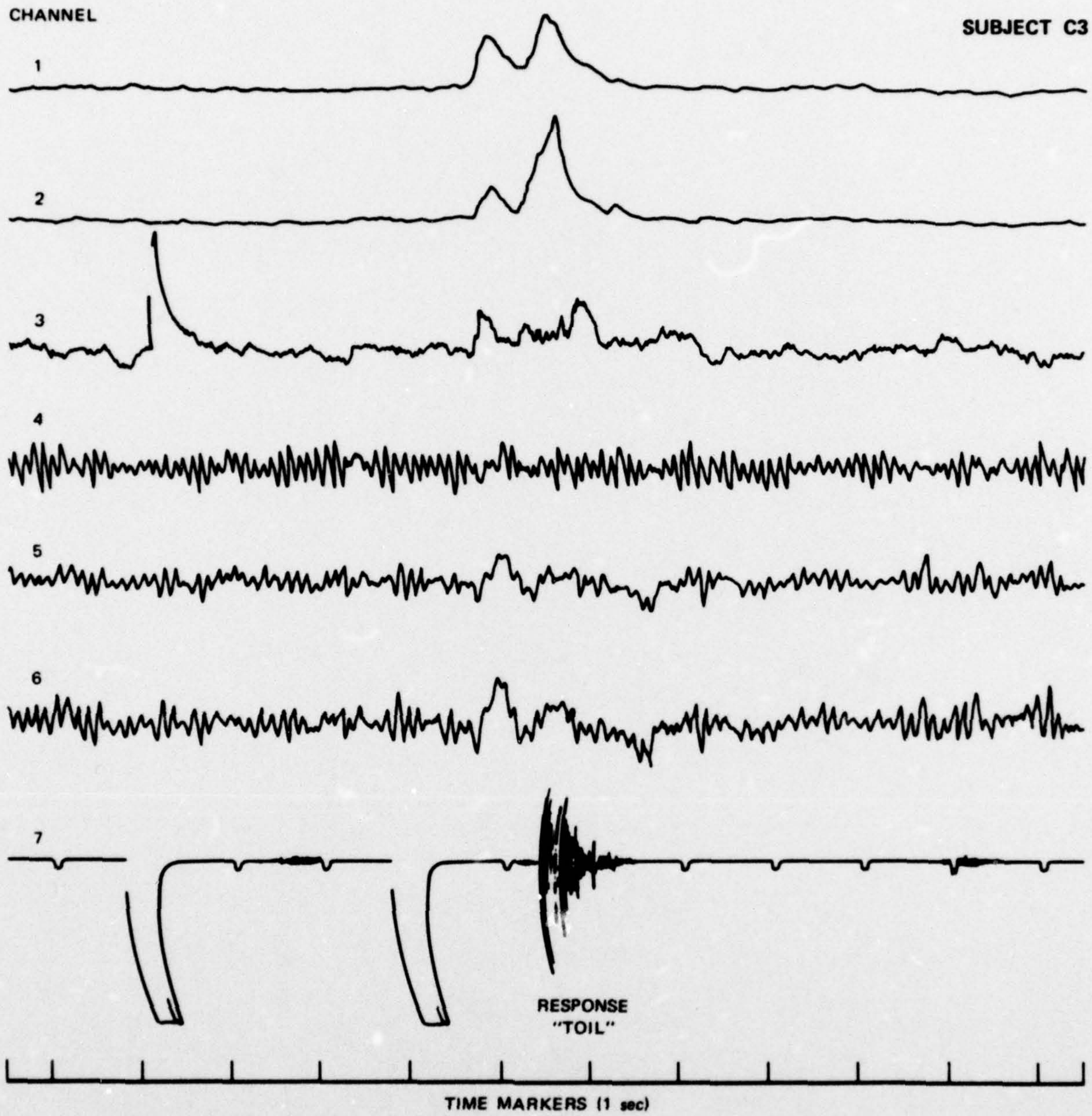


FIGURE 5 DYNOGRAPH RECORDING OF RESPONSE TO AUDITORY STIMULUS, OVERT RESPONSE, EYES CLOSED. Electrodes and symbols the same as Figure 3.

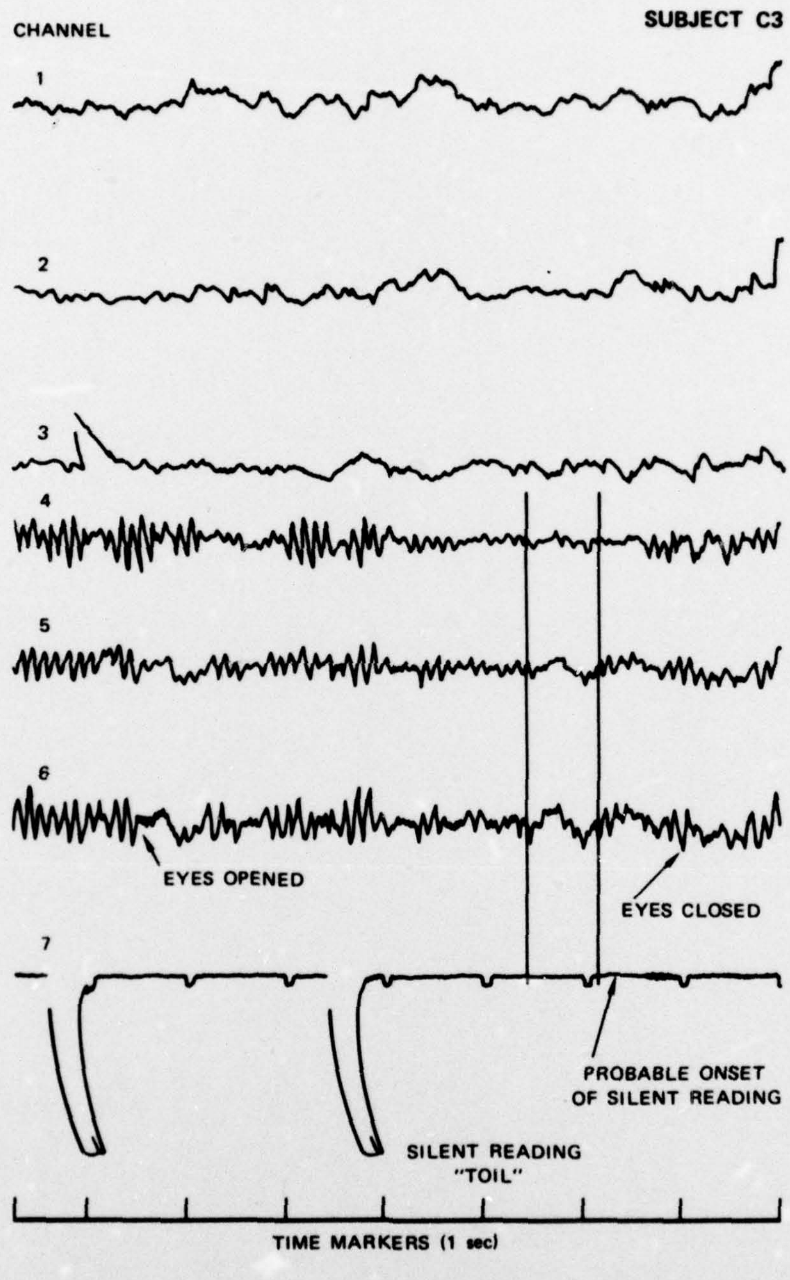


FIGURE 6 DYNOGRAPH RECORDING OF RESPONSE TO VISUAL STIMULUS, EYES OPEN, COVERT RESPONSE (SILENT READING). Electrodes and symbols the same as Figure 3.

and the closing of eyes following the reading as was found in Figure 3, 4, and 5. This at least suggest that for the eyes-open condition, the EEG for <u>covert</u> speech should have a spectra very similar to that of the EEG for <u>overt</u> speech.

Finally, in comparing the EMGs of Figures 3, 4, and 5 for the overt response "TOIL," although marked differences in the patterns exist, there are also obvious similarities. These may be a result of differences in the actual pronunciation of the word, as is suggested by the differences in pattern of the vocalization output shown in channel 7.

<u>EMG Analysis</u>

As described above, initial analysis of EMG records has been done by visually comparing direct overlay tracings of the Dynograph outputs. Figure 7 illustrates the comparison of three EMG electrode outputs for Ss B and C for the same overtly spoken word ("TAKE") on two different experimental days each. Thus, comparisons can be made within a S on two different occasions, between two different Ss for the same word, and between three sets of muscles for the same S and word. Figure 8 illustrates the comparison between two different but similar sounding words ("TONE" and "TON") for the same S during the same recording session.

A comparison of the EMG records for subject C in Figures 7 and 8 show that the EMG patterns are more consistent from one session to another for the same word ("TAKE") than between two similar words ("TONE" and "TON") recorded in the same session. Nevertheless, the EMG patterns for "TAKE" (Figure 7) are not as consistent for subject C on two different occasions as might be expected <u>a priori</u>. This may be due to differences in electrode placement between the two sessions, since in Experiment 2 and with subject B in Experiment 1 (Figure 7), a much closer pattern repeatability is shown, perhaps because of better electrode placement. Note also in Figure 7 that while subject B's EMG responses of "TAKE" on two different occasions are fairly similar, they are quite different from subject C's, verifying that the physiological response patterns are unique for each individual.

Figure 9 compares the EMG patterns for subjects C and B between sessions for sentence 3. The results are essentially the same as for the individual words--namely, that each individual's response is unique, and is more similar from one session to another within a S than between Ss within sentences or between sentences within a S and within a session. By thus comparing the EMG responses to all words for the three Ss for all conditions and over all sessions, it was found that EMG patterns for the muscle groups measured by electrodes 7/8 and 13/16 most consistently reproduced a pattern for the same word.

Finally, Figure 10 (bottom) shows the reconstruction of the EMG response of sentence 3 from the separate responses to the individual words. Comparison of the reconstruction with the naturally spoken sentence (upper portion of Figure 10) illustrates that the pattern of each

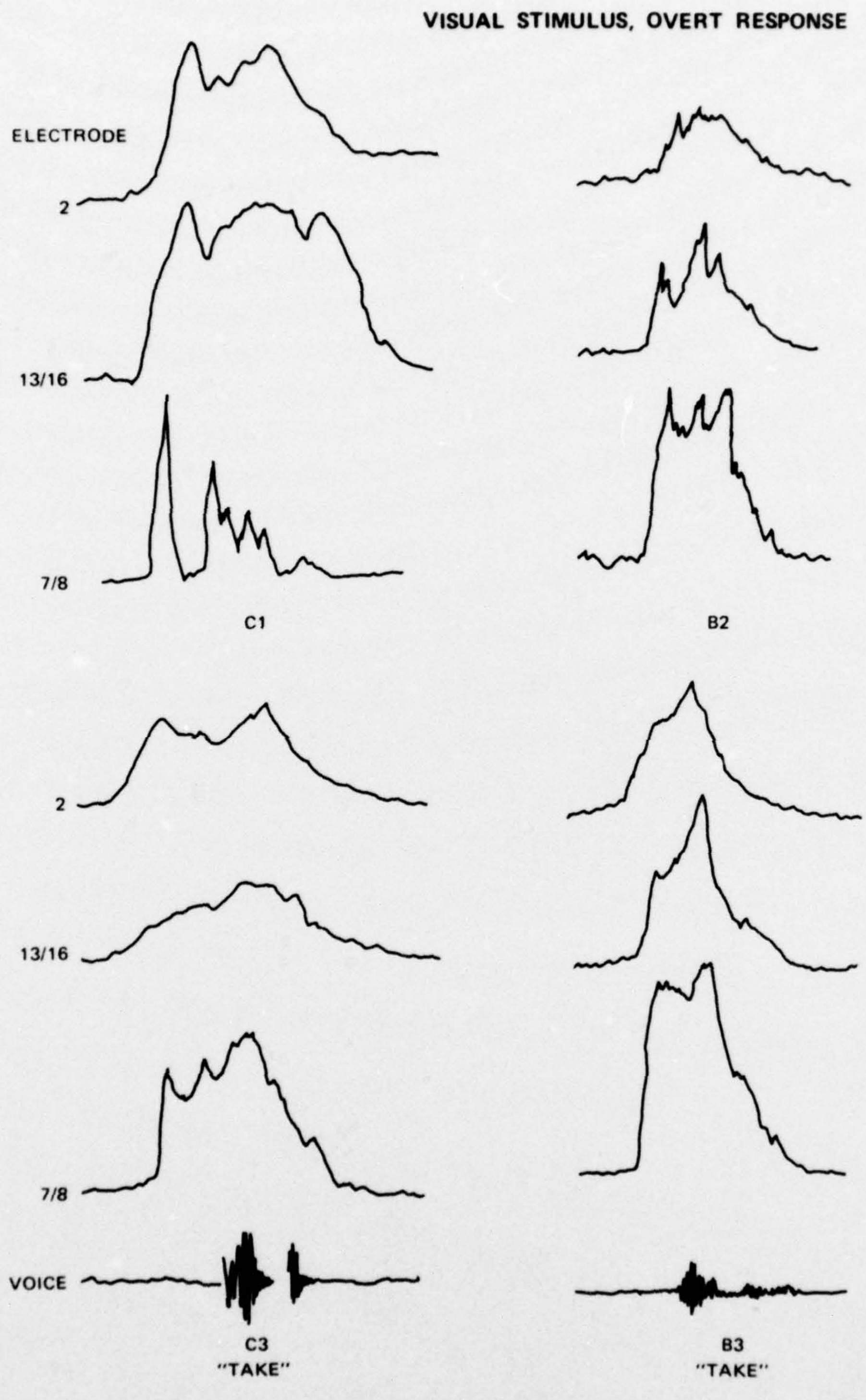


FIGURE 7 COMPARISON OF EMG RECORDS FOR TWO SUBJECTS ON TWO SESSIONS FOR THE OVERT RESPONSE "TAKE"

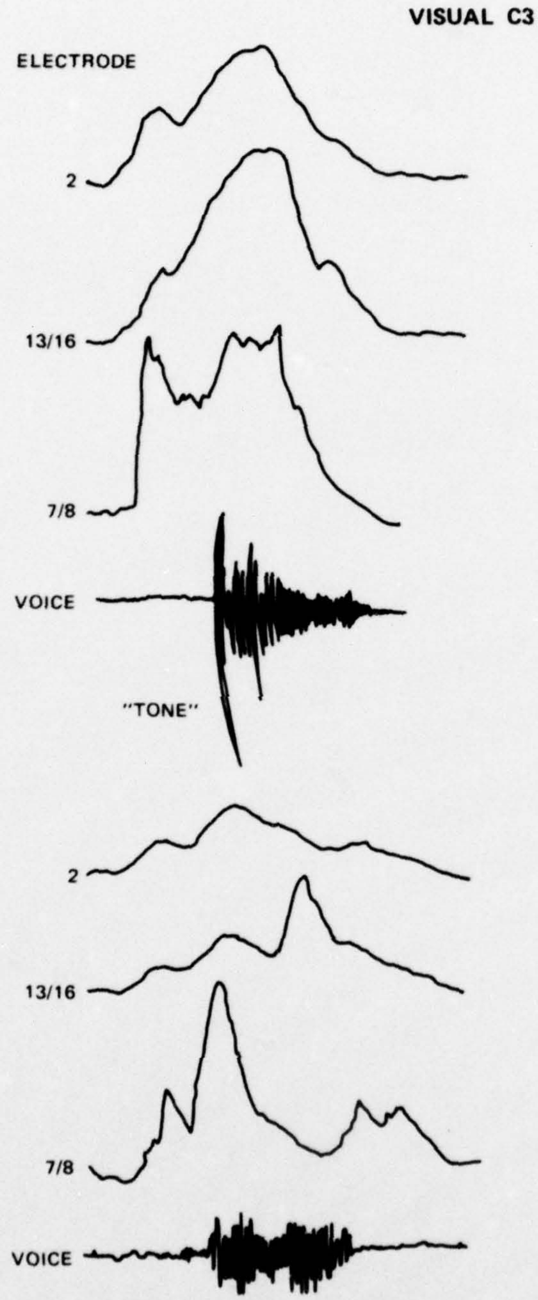


FIGURE 8 COMPARISON OF EMG RECORDS FOR THE SAME SUBJECT IN THE SAME SESSION FOR TWO DIFFERENT BUT SIMILAR WORDS

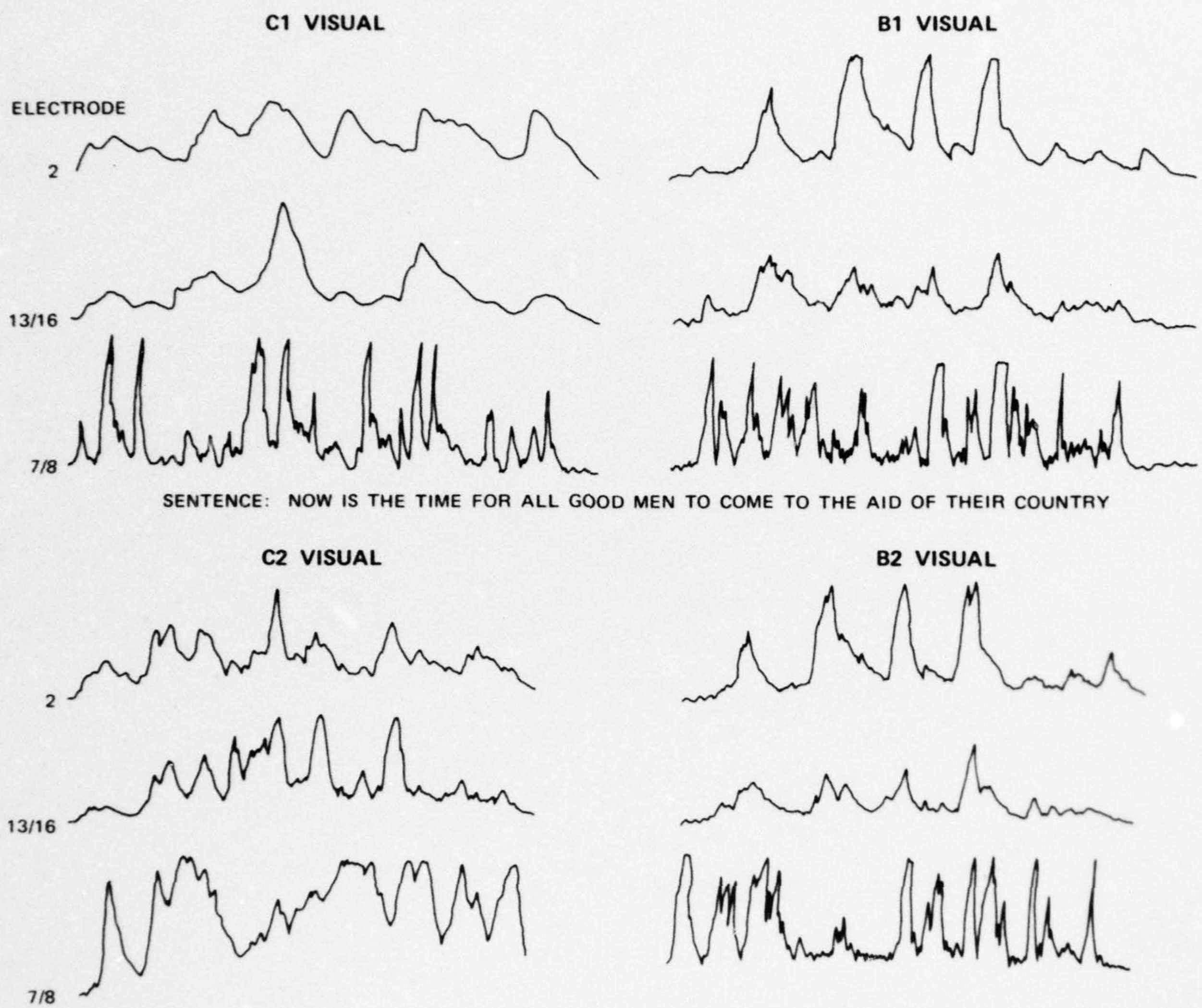


FIGURE 9 EMG PATTERNS FOR TWO SUBJECTS ON TWO SEPARATE SESSIONS FOR A SENTENCE

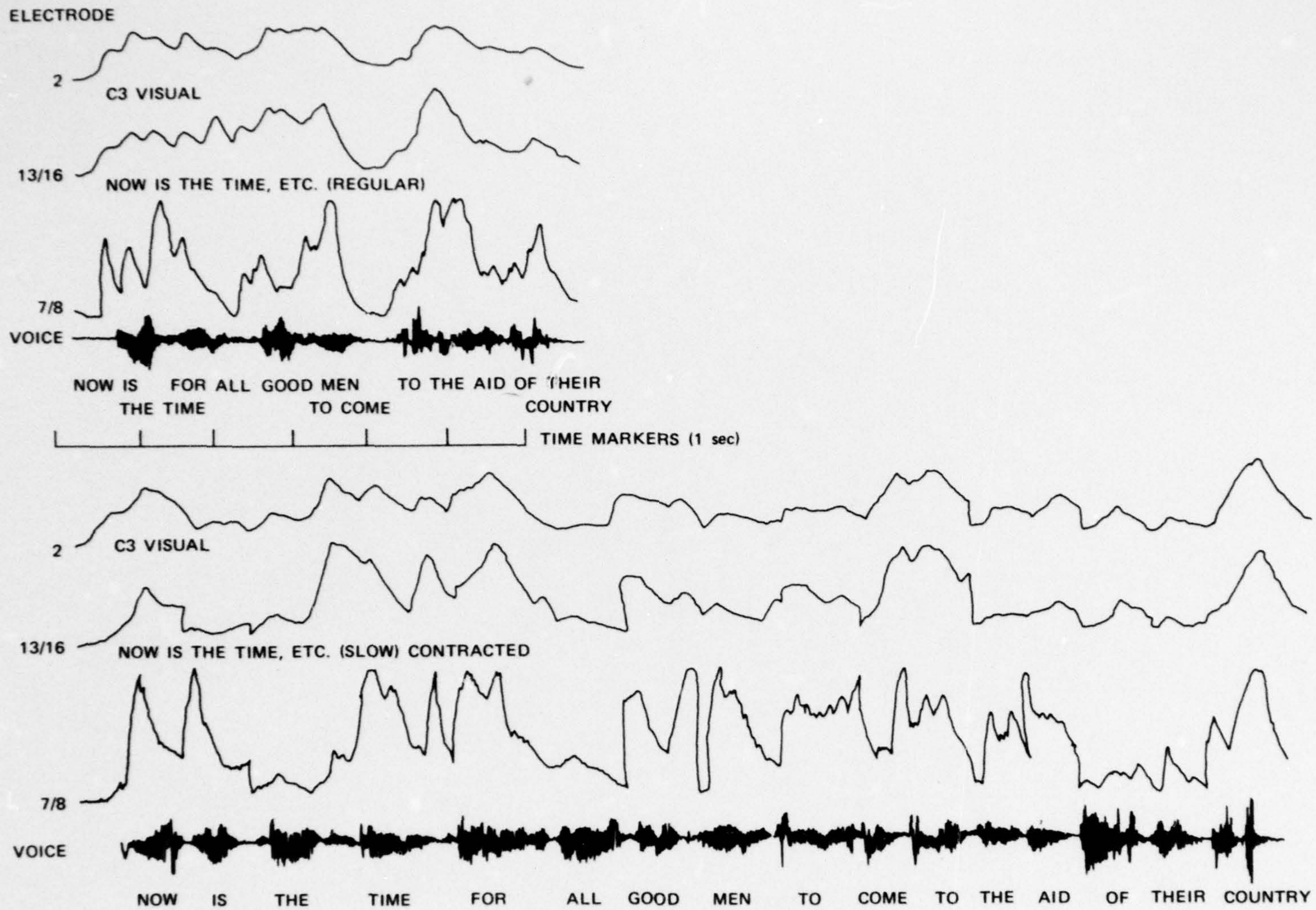


FIGURE 10 RECONSTRUCTION (BOTTOM) OF A SENTENCE FROM EMG RESPONSES TO INDIVIDUAL WORDS COMPARED WITH THE EMG RESPONSES FOR THE NATURALLY SPOKEN SENTENCE (UPPER)

word spoken separately is recognizable in the naturally spoken sentence, even though in the latter each word is preceded and followed by another word. This suggests that individual words may be recognized within a sentence by the computer pattern recognition procedure.

EEG Analysis

The first portion of data collection and analysis is to edit and digitize the data recorded on the analog tape by the Linc-8 computer; however, programs for doing this have only recently been completed (see section Methods, General, above). Therefore, to begin analysis on the CDC-6400 as soon as possible, a time-consuming collateral path was used to digitize the tapes of Experiment 1 (all Experiment 2 tapes are now being edited on the Linc-8). This involved playback of the analog tape on a different model tape recorder (Ampex FR 1300) than was used on initial recording, writing programs for digitizing an entire tape on a XDS 930 computer, and finally writing a separate program on the CDC-6400 computer for locating the data for particular words. In addition, a statistical analysis program supplied by Dr. Gary Galbraith of the University of Southern California had to be debugged and calibrated on the CDC-6400 to analyze the data of the selected words. Five data words were selected for initial analysis and the various statistics for the EEG and EMG, were computed. These compiled data were then analyzed for pattern content in the clustering program. The sampling rate for the digitization was set at 2500 samples/sec/channel (seven channels), and the analog tape was played back at 30 ips, providing an effective sampling rate per channel of 156 samples per sec. This allows frequency resolution of 0-78 hertz. Since the EEG signals below about 2 hertz are not significant for this study, the low end of the spectrum may be ignored for spectral analysis and clustering of the EEG data.

Following several digitization sessions, data for the five selected words (Table 2) were prepared for the clustering analysis. Data selection was based on the appearance of the raw Dynograph record for reproducibility, so that the number of occurrences were included in the clustering analysis.

Table 2

WORDS SELECTED FOR CLUSTERING ANALYSIS,
NUMBER OF OCCURRENCES, AND SEQUENCE OF OCCURRENCE

Word	Number of Occurrences	Sequence of Occurrence
HIT	6	1, 6, 9, 11, 16, 20
COOL	5	2, 7, 12, 17, 21
PUT	4	3, 10, 13, 18
HAD	4	4, 8, 14, 19
HEAD	2	5, 15
	21	

Before calculating the various statistics to be used in the clustering program, several waveform plots of the digitized data were obtained on a CDC-280 microfilm plotter connected to the CDC-6400. This was necessary to show that the digitized data conform to the raw Dynograph record. Figure 11 illustrates such a plot of all seven channels for the word "HIT" in session 1 for S C, the ordinate being arbitrary amplitude and the abcissa the time for 256 samples.

The physiological data of the selected words were then fed into the spectral analysis program to obtain frequency components, cross spectra, linear coherence, and the weighted average coherence functions. These statistics each may contain features for recognition of the physiological components of speech, and so were input to the clustering program in various combinations. In theory, if the quality of information contained in the spectral output has "recognizable features," then the clustering program is capable of classifying the biological potentials according to the selected words. One of the main problems with this analysis, as with any cluster analysis on exploratory data, is the relative scaling of the 33 frequency bin amplitudes in the spectral output. Even if the signals have "features," they may be lost if the choice of a scale is incorrect. For this reason, the data were normalized (as explained in section Methods, General), this being the least-biased relative scaling method.

The initial clustering was carried out on the 21 word occurrences based on the spectral content for frequency and amplitude of the EEG plus EMG, nonscaled; for the frequency and amplitude of the EEG alone, nonscaled; and for the frequency and amplitude of the EMG alone, nonscaled. This was then repeated with the data scaled in two different ways as previously described. An example of the results (for the EMG only condition) are shown in Table 3. Eight separate clusterings were found by first placing all points in one cluster, then partitioning this into two clusters, and so on until eight clusters were obtained. These eight were then "lumped" one cluster at a time until only two clusters remained. Note in this clustering that all the words beginning with an "H" are grouped in the first cluster at the two-cluster level.

A measure of how well the partitioning into clusters describes the data is the distance a given point in a cluster is from the cluster center. This distance can be considered as a "error" score for each data point in the cluster. As an overall statistic for clusteredness, we use the sum of all of the squared errors in a cluster, measured as a percentage of the total squared error of cluster 1 (by definition, 100%). The results on the five selected words are indicated in the fourth column of Table 3, and are also plotted versus the number of clusters in Figure 12 as the "cluster characteristic curve" for these words. Each point on this curve shows the error or variance caused by using only a certain small number of clusters, rather than using one cluster for each word or data object. Note that this latter condition would represent zero error, since each data object would be its own cluster. We arbitrarily define the one cluster (the overall average of the data) error to have a value

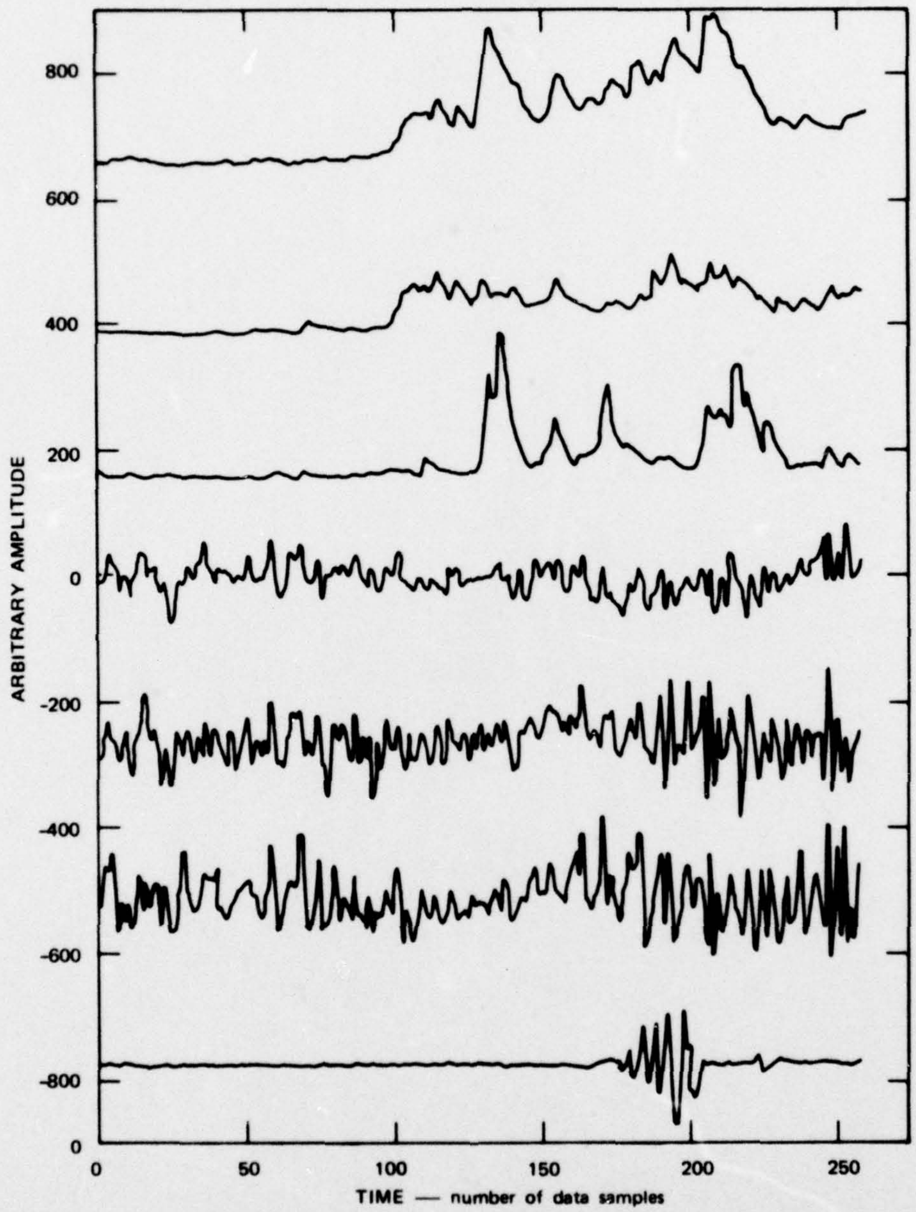


FIGURE 11 COMPUTER PLOT OF SEVEN CHANNELS OF DIGITIZED DATA FOR SUBJECT C1 IN RESPONSE TO THE WORD "HIT." Channels same as in Figure 3.

Table 3

21 WORDS FROM SESSION C1, EMG CHANNELS ONLY (CHANS 1-3)
Bins 3-32 of Frequency Data Not Scaled

Iter	Number of Clusters	Points in Cluster	% Error	Words in the Cluster and Frequency of Occurrence
1	1	21	100%	All points in one cluster
2	2	1-15	56.5532	HIT (6), HAD (4), HEAD (2), COOL (3)
		2-6		COOL (2), PUT (4)
3	4	1-8	32.1759	HIT (2), HAD (3), HEAD (1), COOL (2)
		2-4		COOL (2), PUT (2)
		3-2		PUT (2)
		4-7		HIT (4), HAD (1), HEAD (1), COOL (1)
4	8	1-4	13.9114	HIT (1), HEAD (1), COOL (1), HAD (1)
		2-3		COOL (1), PUT (2)
		3-1		PUT (1)
		4-4		HAD (1), HEAD (1), HIT (1), COOL (1)
		5-1		PUT (1)
		6-1		COOL (1)
		7-3		HIT (3)
		8-4		HAD (2), HIT (1), COOL (1)
5	7	1-8	15.2311	HIT (2), HAD (3), HEAD (1), COOL (2)
		2-3		COOL (1), PUT (2)
		3-1		PUT (1)
		4-4		HAD (1), HEAD (1), HIT (1), COOL (1)
		5-1		PUT (1)
		6-1		COOL (1)
		7-3		HIT (3)
6	6	1-8	17.3050	HIT (2), HAD (3), HEAD (1), COOL (2)
		2-3		COOL (1), PUT (2)
		3-1		PUT (1)
		4-7		HIT (4), HAD (1), HEAD (1), COOL (1)
		5-1		PUT (1)
		6-1		COOL (1)
7	5	1-15	23.7602	HIT (6), HAD (4), HEAD (2), COOL (3)
		2-3		COOL (1), PUT (2)
		3-1		PUT (1)
		4-1		PUT (1)
		5-1		COOL (1)
8	4	1-15	29.0901	HIT (6), HAD (4), HEAD (2), COOL (3)
		2-4		COOL (2), PUT (2)
		3-1		PUT (1)
		4-1		PUT (1)
9	3	1-19	57.9038	HIT (6), COOL (5), HAD (4), HEAD (2), PUT (2)
		2-1		PUT (1)
		3-1		PUT (1)
10	2	1-20	72.7829	HIT (6), COOL (5), HAD (4), HEAD (2), PUT (3)
		2-1		PUT (1)

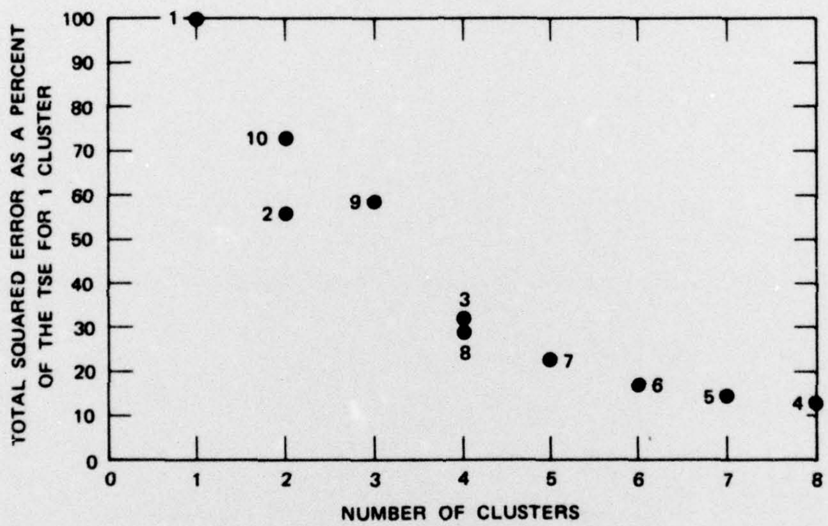


FIGURE 12 CHARACTERISTIC CLUSTER CURVE FOR THE EIGHT CLUSTERS FOR SUBJECT C1 (From Table 3)

of 100%. The cluster characteristic curve shows how much the error drops as more clusters are used to describe the data.

Thus, Table 3 and Figure 12 suggest that the five selected words may be grouped and compared with a theoretically perfect clustering. That is, are there five clusters, each containing all incidences of a particular word? In this manner, it ideally might be found that cluster 1 of the five clusters contains all the occurrences for the word HIT, cluster 2 for the word COOL, cluster 3 for the word PUT, cluster 4 for the word HAD, and cluster 5 for the word HEAD. With additional analysis from Experiment 2, with its more rigidly structured data collection we expect the quality of the data to improve, and therefore the clustering to be more selective.

Results: Experiment 2

General

Experiment 2 was designed to refine Experiment 1 to obtain more accurate data that might qualify for the clustering pattern recognition program. First it was decided to choose fewer words than previously employed, and to select words that had the greatest likelihood of reproducing consistent EMG patterns. Second, words were repeated ten times during each of two recording sessions for each of the three Ss, all under the visual presentation condition of Experiment 1. Third, electrode sites were restricted to the six that could be recorded simultaneously, including two EMG and four EEG (see Methods Apparatus, Electrode Placements). Fourth, five additional bisyllabic, phonetically balanced words were added to the language task, with the accent first on one syllable and then on the other. The words and the sentence that was overtly read at the end of each word list are shown in Table 4. The 15 words were chosen to emphasize rounded lips, bilabials, and open lips in the case of the monosyllables, and to asses the contribution of the lead part of a bisyllabic word on the second part (and vice versa) when one syllable is accented. Finally, no covert responses were obtained in Experiment 2.

Figure 13 illustrates the raw record of the word "COOL" by Subject C on session 6. This record is much like that of Figure 3, except that now there are two integrated EMG channels and four EEG channels. The stimulus response paradigm is also the same as in Figure 3--namely, that the S is resting with eyes closed before a visual word presentation. On a "ready" signal, she opens her eyes and attends to the screen. On stimulus presentation, she overtly reads the word into the microphone and then closes her eyes again to await the next word.

Note in Figure 13 that the same general results were found as described above for Experiment 1. That is, the EEG is synchronized until after the eyes are opened following the ready signal, and then remains desynchronized until the eyes are closed. Second, the EMG begins to increase about 2/5-3/5 sec before the actual vocalization.

Table 4

LANGUAGE TASK FOR EXPERIMENT 2

	Bisyllabic	
Monosyllabic	Accent First Syllable	Accent Second Syllable
TIP	BLACKBOARD	BLACKBOARD
HIT	SCHOOLBOY	SCHOOLBOY
HAD	COUGHDROP	COUGHDROP
PUT	SHIPWRECK	SHIPWRECK
COOL	MOUSETRAP	MOUSETRAP

Sentence:

THE SHIPWRECKED SCHOOLBOY HAD PUT A COOL COUGHDROP IN THE MOUSETRAP AND AIMED IT TO HIT AND TIP OVER THE BLACKBOARD.

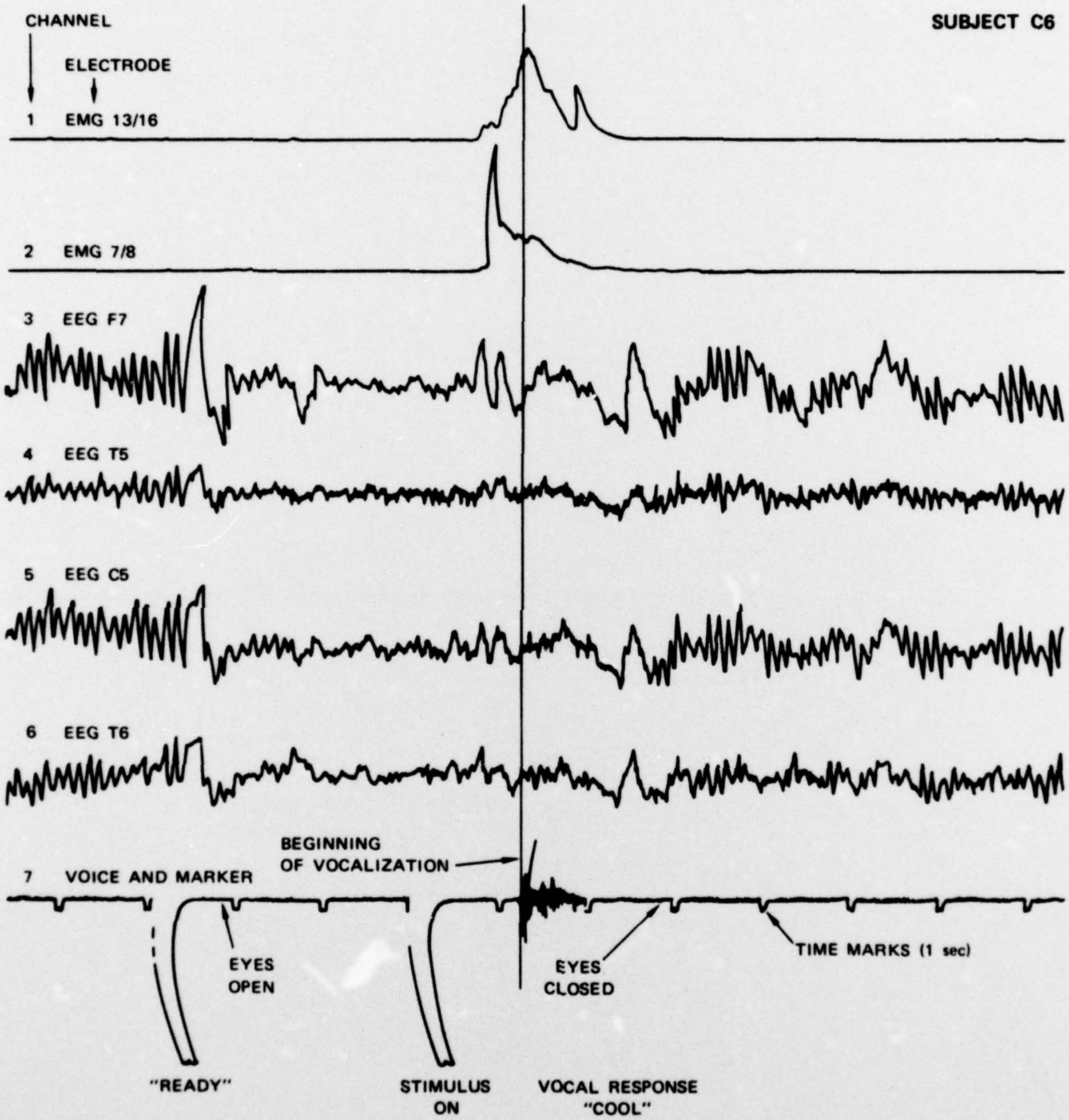


FIGURE 13 DYNOGRAPH RECORDING OF STIMULUS-RESPONSE OF EMG AND EEG FOR THE WORD "COOL"

Third, in all EEG channels, but especially in the dominant (speech) hemisphere (in particular, over Broca's area, electrode F7), the slow-wave, negative/positive potential is present with the onset of the EMG increase. Interestingly, for this subject, this slow-wave appears again in the EEG following the end of the EMG changes and just before the eyes are closed. The significance of this result is unknown at this time, but if this potential remains consistent for covert responses as well (as it did in Experiment 1), it may serve as a feature detector in the cluster analysis program.

EEG cluster analysis of these data is awaiting tape editing and digitization on the Linc-8, which should be completed by December.

EMG Analysis

Figure 14 shows the results of multiple (N=5) EMG tracings of the 15 stimulus words for the fifth session of Subject C. The vertical line in each set of tracings marks the beginning of vocalization. These multiple tracings show that the EMG variability for a given muscle group and for a given word is significantly less than that between words and between muscle groups. They also show that the temporal variability is slightly larger than the magnitude variability. Some words like PUT, MOUSETRAP, BLACKBOARD show much less variability than others.

In any event, both the temporal and amplitude variability within a word and within a muscle group are sufficiently low that an average response may confidently be drawn to represent the EMG response to a given word. Such average curves from Figure 14 are drawn in Figure 15 for C5. The averages of bisyllabic words for C5 may be compared with the bisyllabic words for B5 and B6 (Figures 16 and 17) for between S variability, and between B5 and B6 for within S variability. Such a comparison reveals again that the EMG response for a given S is unique; however, the responses between subjects C and B for the words "COUGHDROP," "BLACK BOARD," "BLACKBOARD," and "SHIPWRECK" are fairly similar. Comparisons within a subject between sessions (Figures 16 and 17) shows relatively small variability, while comparisons between words accented on the first syllable and those accented on the second shows less variability than might be supposed *a priori*.

Finally, Figure 18 illustrates multiple tracings for Subject B, on her fifth session, for the sentence. Note that even here, where each sentence may be spoken at a slightly different rate, the magnitude variability is relatively small, and even the temporal variability is low during the first portion of the sentences. Furthermore, a comparison of the sentence components of Figure 18 with the overt response of the individual words of Figure 16 shows that roughly 80% of the EMG patterns within the sentence can be picked out visually by knowledge of the average response of the single word.

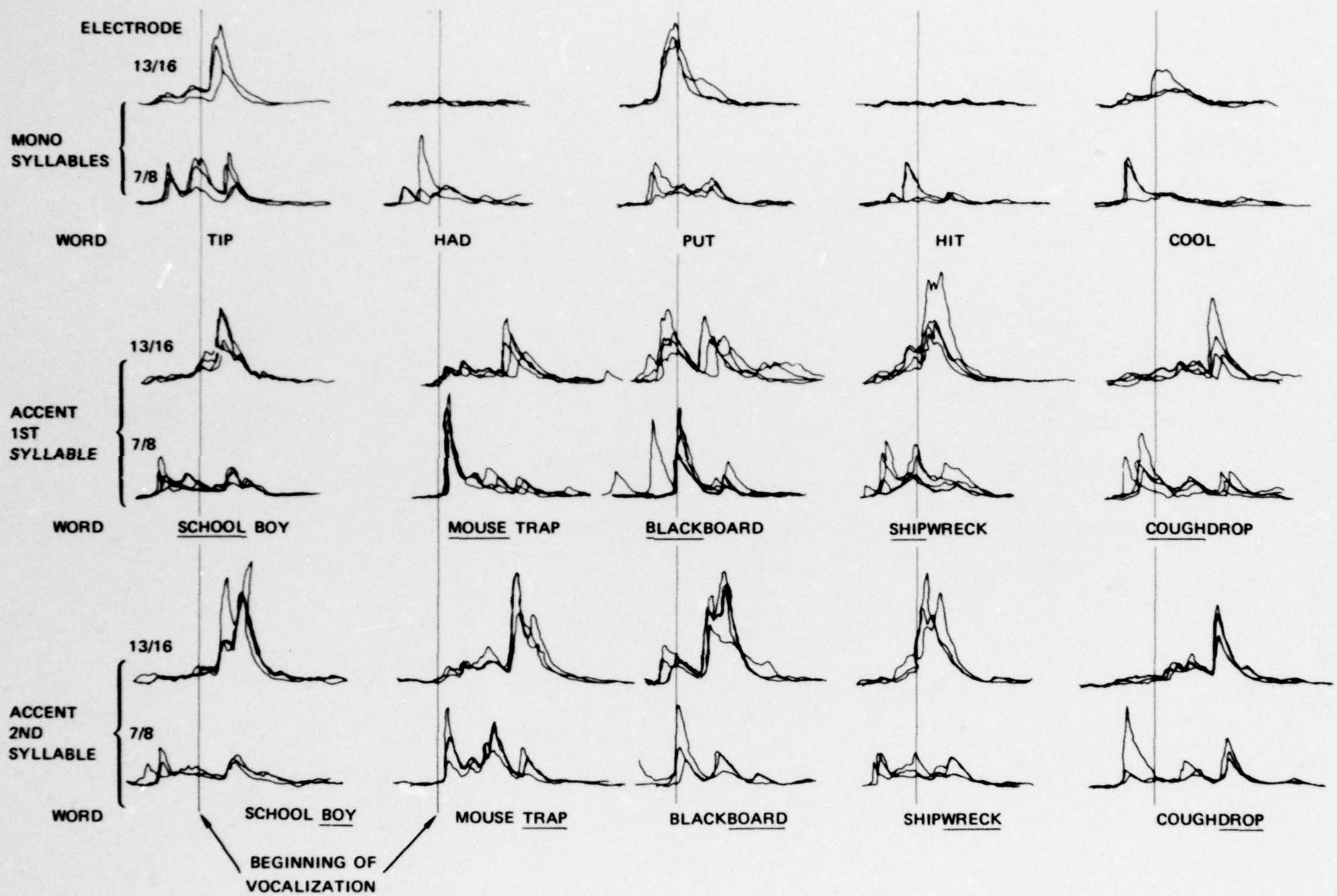


FIGURE 14 MULTIPLE (N = 5) TRACINGS OF THE EMG PATTERNS FOR 15 STIMULUS WORDS, SESSION 5, SUBJECT C. Vertical lines indicate beginning of vocalization.

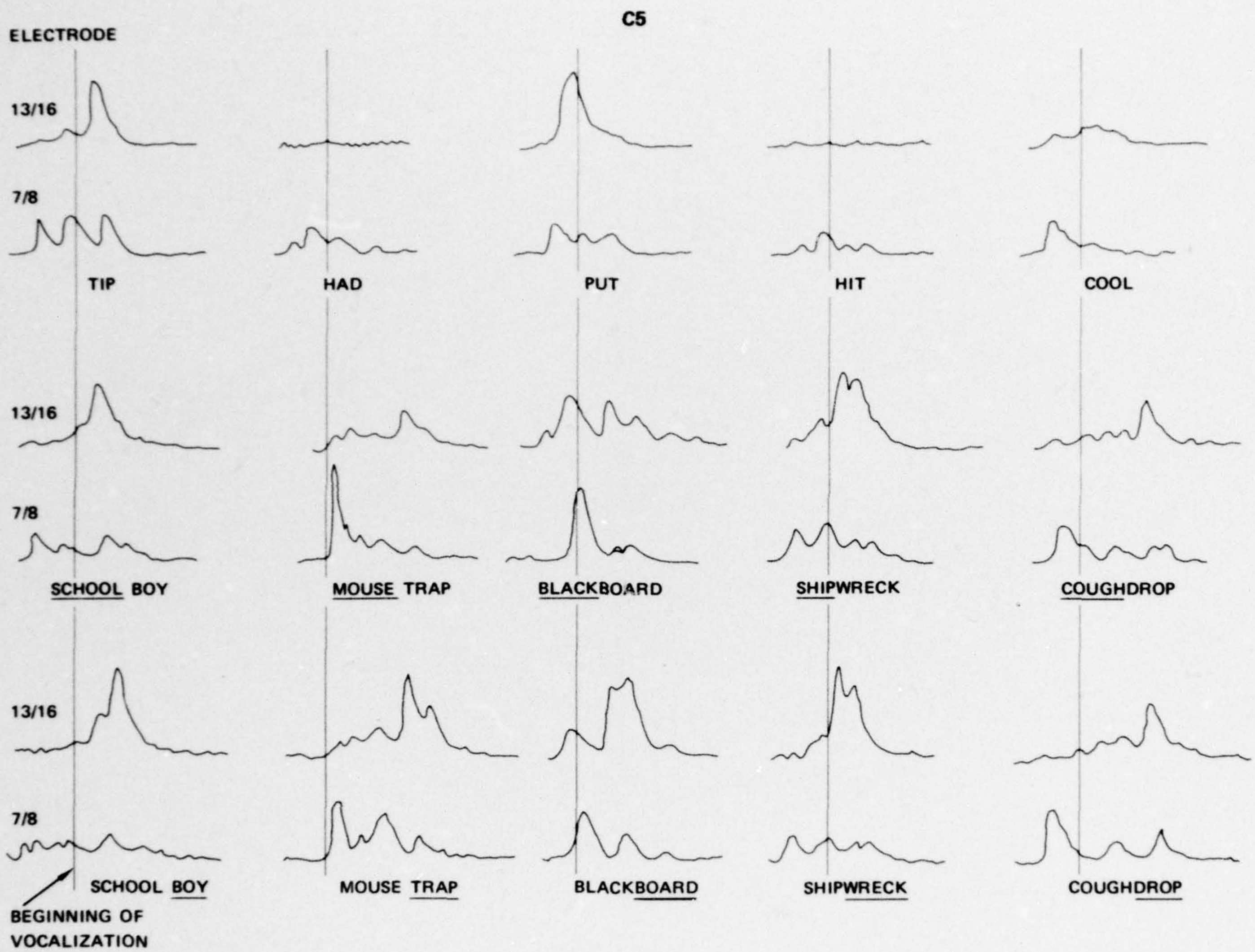


FIGURE 15 AVERAGE OF EMG RESPONSES OF MULTIPLE TRACINGS OF FIGURE 14

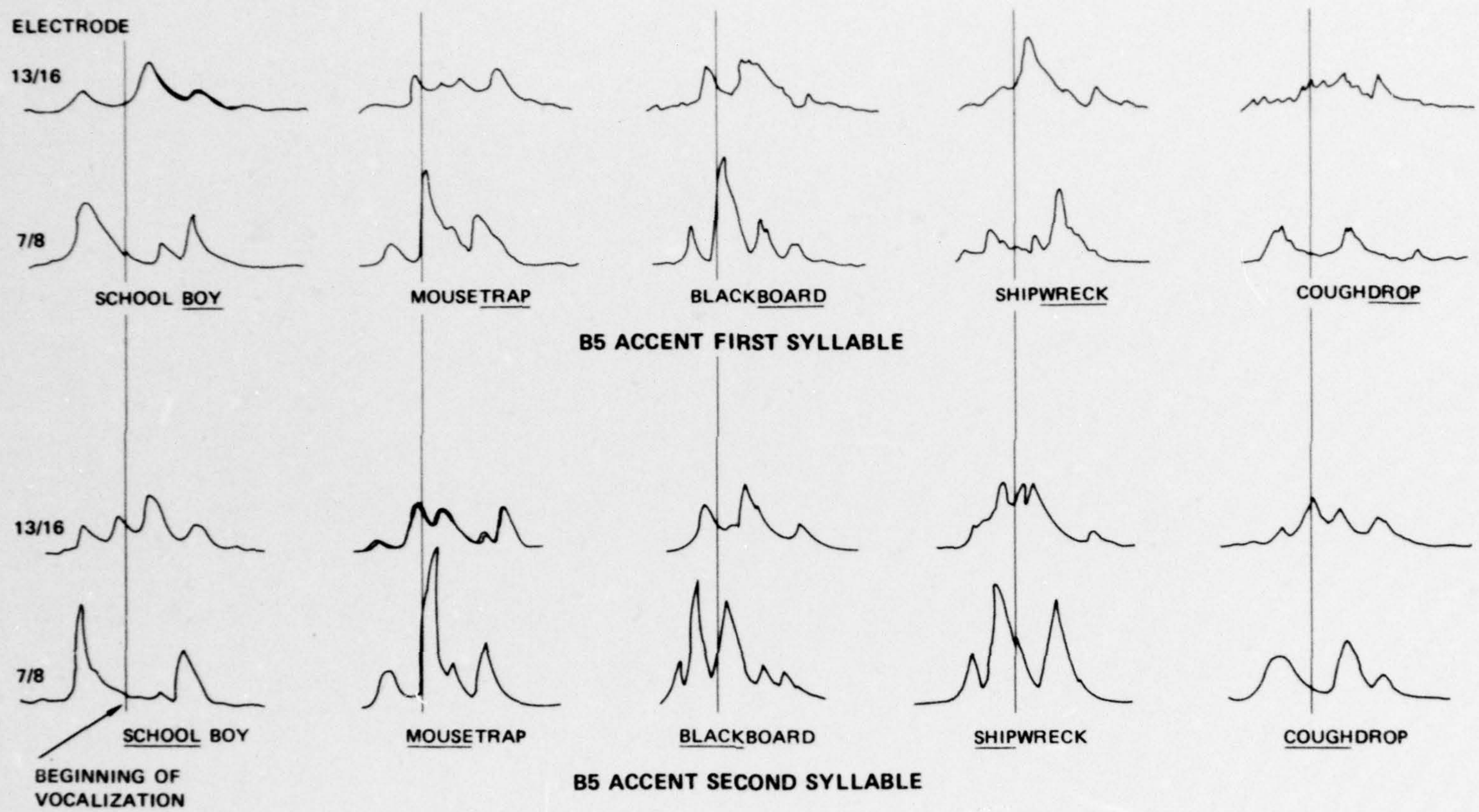


FIGURE 16 AVERAGE EMG RESPONSES FOR BISYLLABIC WORDS FOR SUBJECT B, SESSION 5, COMPARING ACCENTS ON THE SECOND SYLLABLE WITH ACCENTS ON THE FIRST SYLLABLE

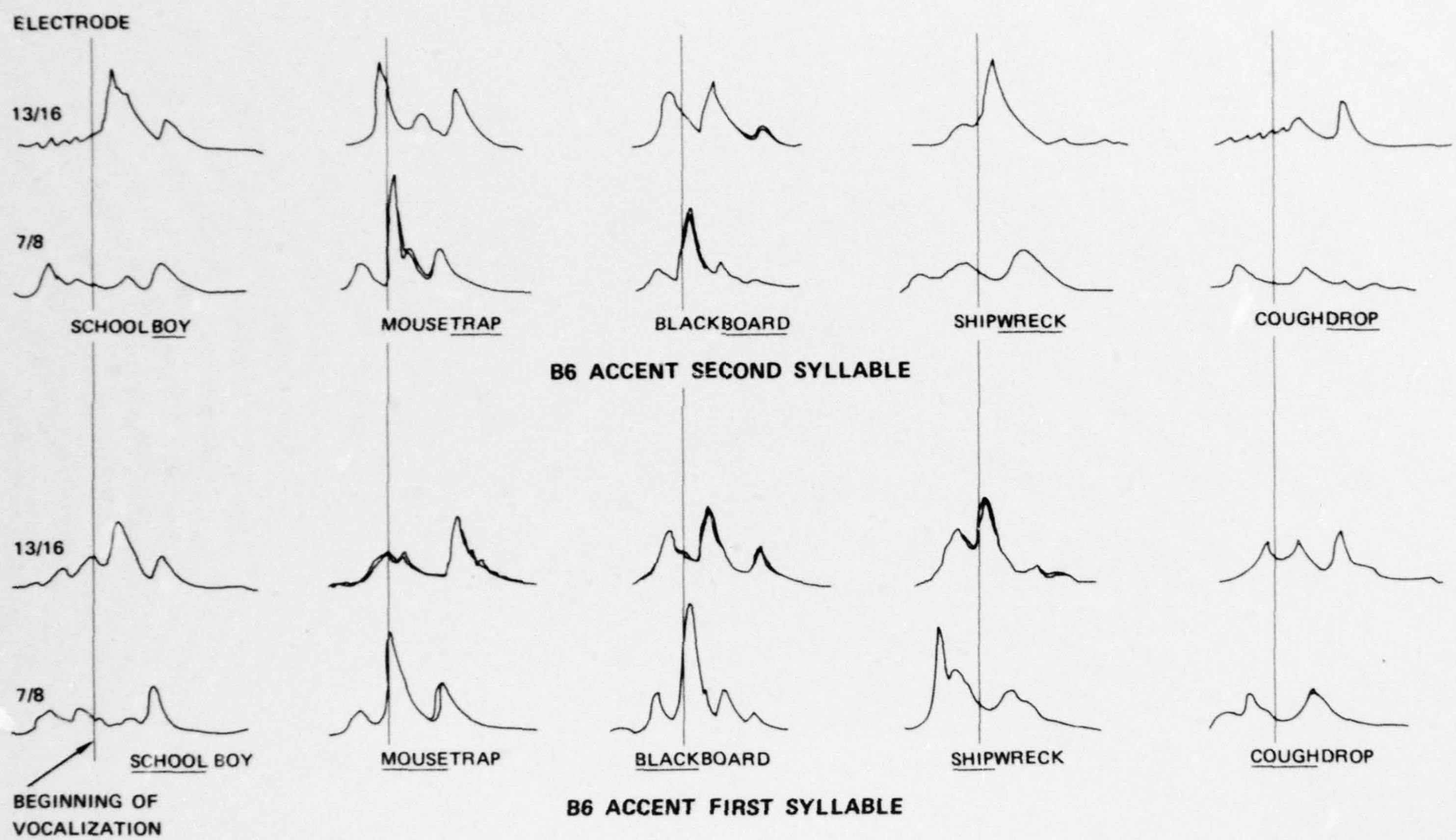


FIGURE 17 SAME AS FIGURE 16 FOR SUBJECT B, SESSION 6. Compare with Figure 16 for within-subject variability.

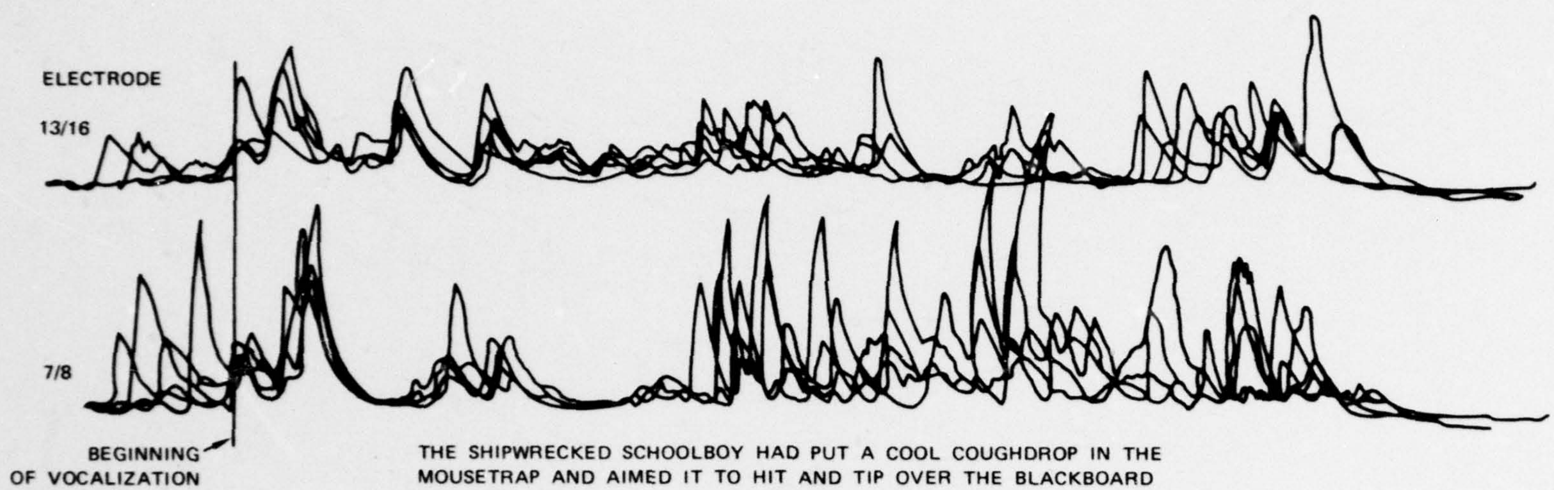


FIGURE 18 MULTIPLE EMG TRACINGS OF OVERT RESPONSE TO A SENTENCE FOR SUBJECT B, SESSION 5

Discussion and Conclusions

The objectives of the first year of this project were to establish the validity of the basic premise that patterns of biological information can be related to covert language behavior (thought). We might restate this by asking several specific questions:

(1) Are integrated EMG patterns of spoken words consistent within words and over time within a subject? If so, are they unique for a given subject for a given word? If so, do they follow linguistic laws?

(2) What statistic of the EEG corresponds sufficiently with the EMG pattern of speech to use as a feature detector in a pattern recognition program for a given word?

(3) Given this EEG statistic, can it distinguish one spoken word from another? Can it identify a given covert word? Can it select a word from an overt or covert sentence containing the word, even when different words precede and follow the test word?

The results of the first six months of the research reported above for Experiments 1 and 2, although not conclusive, support an affirmative response for the first set of questions. The significant results may be summarized as follows:

(1) The EMG patterns for each word used thus far in this research are specific for that word.

(2) The EMG patterns for a given word are consistent, showing less within subject variability than between subject variability.

(3) Amplitude variability of an EMG pattern for a given word is moderate, but slightly more than the temporal variability. However, both types of variability are sufficiently small so that an average pattern can be obtained that reliably represents the word.

(4) The average EMG response of a given word for a given subject can be used as a template to identify the same EMG response for that word when the word is imbedded in a sentence.

(5) The variability of bisyllabic words between those accented on the first syllable and those accented on the second is greater than the within variability for a given bisyllabic word, and greater than the variability for monosyllabic words. However, this accent variability is still sufficiently small so that either accented word may be used to identify the same unaccented bisyllabic word when it is imbedded in a sentence.

Answers to the set of questions on the EEG are still not complete. We are assuming for now that if the EMG patterns are consistent for the overt response, as they are, then the EEG for the covert response should be similar to that of the overt response to the same word. Evidence from the raw record EEGs both with respect to frequency differences of synchronized versus desynchronized patterns and the existence of the slow-wave, negative/positive potential for the covert and overt responses suggest that such a correlation is quite possible. In addition, the pattern recognition program so far has been able to select those words beginning with an "H" from other words in Experiment 1, using clustering of several EEG statistics. These statistics are the cross- and auto-spectra, the linear coherence function, and the weighted-average coherence. The one that will serve best as a feature detector is yet to be determined.

During the next six months, with the improved Linc-8 tape-editing and digitizing of the data of Experiment 2, we expect to answer the questions involving the EEG. By December 1, our turnover time for data analysis should be reduced to one day. Based on our results with the EMG, we are fairly confident that we will be able to establish definitively whether the EEG alone can provide us with sufficient information to identify language behavior.

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